Mutual Interaction of Soil Moisture and Climate Dynamics (NAGW-4164)

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Introduction

The land surface and the atmosphere exchange water and energy through the turbulent sensible and latent heat fluxes and radiative transfers. The magnitude of each of these exchanges depends on the temperature and moisture states of both the land surface and the atmosphere. Typically, in hydrological studies the atmospheric conditions are assumed to be known whereas the inverse is true for meteorological studies. Although on small spatial scales the meteorological conditions can be considered as independent of the land surface, with increasing spatial scales the signature of the land-surface on the conditions in, especially, the planetary boundary layer (PBL) becomes clearly significant. Therefore, by studying either the sub-surface or the atmospheric branch of the land-atmosphere interface (i.e. a one-way coupled system), one possibly neglects many feedbacks that are present because of the mutual interaction of the soil and PBL states.

The land surface and the planetary boundary layer (PBL) form a coupled system: the exchanges of water and energy depend on as well as change the temperature and humidity profiles in both. In this report we present a mixed-layer model of the PBL which is more complete with respect to the parameterization of the radiative fluxes (Brubaker and Entekhabi, 1996a,b). In addition, the model contains a parameterization (Smeda, 1979) of the growth and collapse of the PBL. The model is verified using measurements of the FIFE field experiment (Kim and Entekhabi, 1998a).

Model Development

The core of the model consist of the budget equations for soil temperature (T_s), mixed-layer potential temperature (θ), mixed-layer specific humidity (q) and soil moisture (s):

$$
\begin{aligned}
z_t C_{s,i} \frac{dT_s}{dt} &= R_s(1-a) + [R_{ad}(1-\epsilon_a) + R_{sd}]\epsilon_s - R_{gu} - H - \lambda E \\
\rho c_p h \frac{d\theta}{dt} &= [R_{ad} + R_{gu} + (R_{ad}(1-\epsilon_a) + R_{sd})(1-\epsilon_s)]\epsilon_a -
\end{aligned}
$$

$$
\begin{aligned}
& R_{sd} - R_{su} + H + H_{TOP} \\
\rho h \frac{dq}{dt} &= E + E_{TOP} \\
z_w \vartheta_s \frac{ds}{dt} &= -\frac{E}{\rho_w} + Q_p
\end{aligned}
$$

The height of the PBL has a strong diurnal evolution. During the day the PBL grows, mainly in response to the virtual heat flux at the land surface. When the virtual heat flux vanishes, the turbulence dissipates and the PBL collapses. The growth of the PBL is governed by

$$
\frac{dh}{dt} = \frac{2\left(u_*^2 u - u_*^2 u \left(1 - e^{-\xi h}\right) - \delta 0.4 \left(\frac{gh}{\theta} \frac{H_v}{\rho c_p}\right)\right)\theta}{gh\delta_\theta} + \frac{H + 0.61\theta c_p E}{\rho c_p \delta_\theta}
$$

with $\delta = 0$ in stable conditions and $\delta = 1$ in unstable conditions.

The mixed layer is capped by inversions in the potential temperature and specific humidity profiles. The strengths of these inversions, δ_θ and δ_q, determine the entrainment of the, normally warm and dry, overlying air:

$$
\begin{aligned}
E_{TOP} &= \rho \delta_q \frac{dh}{dt} \\
H_{TOP} &= \rho c_p \delta_\theta \frac{dh}{dt}
\end{aligned}
$$

Due to entrainment, the inversion strengths themselves change over time however according to

$$
\begin{aligned}
\frac{d\delta_q}{dt} &= \gamma_q \frac{dh}{dt} - \frac{dq}{dt} \\
\frac{d\delta_\theta}{dt} &= \gamma_\theta \frac{dh}{dt} - \frac{d\theta}{dt}
\end{aligned}
$$

The lapse rates γ_q and γ_θ are forcing parameters.

Model Verification

The above model is entirely forced by only the incoming shortwave radiation, the lapse rates γ_θ and γ_q and the observed lateral windspeed.

The model has been extensively verified using observations of three so-called 'golden days' during the First ISLSCP Field Experiment (FIFE). Figure 1 shows some of the verification results of the complete model (i.e. including the collapse of the PBL and evolution of the nocturnal PBL) for August 15, 1987. The lapse rates γ_θ and γ_q, the windspeed and the initial atmospheric conditions were determined from the radiosonde measurements. The friction velocity u_* was determined according to observations. Figure 1 shows realistic diurnal behavior of the model. We also compare the model results with the spatially average surface measurements compiled of FIFE (Kim and Entekhabi, 1998a,b).

Analysis of Feedback Mechanisms

In order to adequately test the response of land surface models to its parameters and forcing variables, it is necessary to allows for turbulent as well as radiative feedbacks. Failure to do so may result in model sensitivities that are not only wrong in magnitude but in sign as well. The impact of feedbacks in the uncoupled and coupled land surface and mixed layer equilibrium energy budgets may be examined using the analytical model. The PBL responds to changes in the surface energy fluxes and it greatly reduces the sensitivity of the surface energy budget to the surface control on turbulent flux such as $\frac{dH}{dr_{s,\min}}$ and $\frac{\lambda dE}{dr_{s,\min}}$. Stomatal resistance depends on photosynthetically active radiation, specific humidity deficit and a minimum value $r_{s,\min}$. We here investigate the response of the model to a change of $r_{s,\min}$. Increasing the stomatal resistance decreases the evaporation. This in return warms up the soil, and increases the sensible heat flux and outgoing longwave radiation, while also increases the humidity deficit $q^*(T_s, p_s) - q$, which opposes the evaporation decrease. Because of the larger outgoing longwave radiation, the net radiation decreases from which it follows that the decrease of evaporation has to be larger than the increase in sensible heat flux. This can be observed in Figure 2, where the sensitivities $\frac{\lambda dE}{dr_{s,\min}}$ and $\frac{dH}{dr_{s,\min}}$ are shown for a range of equilibrium temperatures θ^*. Note that the sensitivities increase with θ^* (Kim and Entekhabi, 1998a).

When the atmosphere does not respond to changes in surface fluxes, the only feedback present is the reduced decrease of evaporation due to the higher soil temperature. A responding PBL, however, leads to a myriad of feedbacks. The increased sensible heat flux and outgoing longwave radiation now warm the atmosphere and decrease the temperature difference that drives the sensible heat flux. The warmer atmosphere emits more longwave radiation towards the surface. The net result is a longwave radiative feedback that partly compensates the increased outgoing longwave radiation. The smaller increase of sensible heat flux is balanced by the latent heat flux that now decreases only slightly when increasing the stomatal resistance, over the entire temperature range (see Figure 2). In summary, the sensible heat flux acts to efficiently tie the two temperature states together, thereby greatly reducing the sensitivity of the model to changes in the stomatal resistance. The results clearly indicate that omission of the feedbacks that arise because of a responding mixed layer results in a significant overestimation of the effect of a change in stomatal resistance.

Effects of Soil Heterogeneity

In coupling the land surface and the PBL, one invariably runs into the problem of heterogeneity along the land surface. The most common route taken around this is the specification of large scale mean or effective parameters, as is done for example in the big leaf soil-vegetation-atmosphere-transfer schemes (SVATs). Due to the nonlinearity of the processes involved, mean parameters are by definition invalid and effective parameters are unlikely to be effective under all conditions and for all fluxes.

Here we examine the impact of soil heterogeneity on the development of the PBL and the subsequent effect of the PBL response to the heterogeneity of the surface fluxes. We examine the impact of heterogeneity of the hydraulic properties present within three soil types. This type of heterogeneity is characterized by small correlation scales ($10^0 - 10^2$ m). This scale is much smaller than the scale of the main boundary layer eddies and heterogeneity of the surface fluxes is therefore assumed to be averaged out by the PBL.

It is worthwhile to examine statistical indicators that characterize spatial heterogeneity of the surface flux rather than soil moisture itself. This will provide insight in the ultimate impact of soil spatial heterogeneity.

Figure 3 shows the time evolution of the histogram of the daily mean latent heat flux for clay soil (kim and Entekhabi, 1998b). It can be seen that over time, probability mass typically moves from higher to lower latent heat fluxes. However, from day 190 onwards, one can see probability mass moving to higher values as well. The mean, median, minimum and maximum values indicated above the histogram will be used to characterize the surface flux heterogeneity in a more condensed fashion.

The most striking feature of all the graphs is that the maximum latent heat flux first decreases, only to increase later. The slight decrease is caused by cooling of the soil due to evapotranspiration and an increase of the surface albedo due to drying of the soil. The increase of the latent heat flux is because drying of the surface causes a higher, drier and warmer mixed layer and causes an increase of the latent heat flux. Following the same logic for the results here, the decrease of the latent heat flux over a (large) fraction of the considered area leads to a drying and warming of the PBL. This causes the sensible heat flux to decrease and the latent heat flux to increase over the (small) fraction where evapotranspiration is limited by available energy rather than soil moisture. Thus, in case of spatially heterogeneous surface fluxes, drying over one (relatively dry) region enhances the drying over the other (relatively wet) region, thereby reducing the heterogeneity of the surface fluxes (negative feedback).

It is useful to draw a parallel with the heuristic complementary relationship introduced by Bouchet-Morton which states that the potential evaporation under stressed (i.e. 'non-potential') conditions is higher than under unstressed (i.e. potential) conditions. Kim and Entekhabi (1997) use the coupled land-PBL model to explain the empirically two concepts.

Lateral Transport

So far the coupled land and PBL model accounts for major vertical fluxes of heat and moisture. It also accounts for vertical radiative fluxes that dominate the thermodynamic equation for the system. There are nonetheless important lateral transports that are forced by gradients in the model potential temperature prognostic, e.g. the zonal and meridional potential temperature gradient $\left(\frac{\partial \theta}{\partial y}, \frac{\partial \theta}{\partial y}\right)$. The energy and vapor transport associated with the PBL winds generated by these gradients are (in complex notation):

$$F_E = \int_{z_{surf}}^{h} \rho q (u + iv)\, dz$$
$$F_H = \int_{z_{surf}}^{h} \rho c_p T (u + iv)\, dz$$

where $u(z)$ and $v(z)$ are the total zonal and meridional winds, h is the height of the local boundary layer, z_{surf} is the elevation of the surface from MSL. The temperature gradients are due to land surface processes as well as PBL conditions. The convergence of heat and moisture over an area are: $\nabla \cdot F_H$ and $\nabla \cdot F_E$. We are particularly interested in the meridional plane flows forced by $\frac{\partial \theta}{\partial y}$. Diurnal osciallations may result from differential amplitudes of surface and PBL temperatures with latitude. An example of such a system is the U.S. Midwest Low Level Jet (LLJ) which transports much of the vapor for central Great Plains precipitation.

Our hypothesis that land-atmosphere coupling and the meridional hydroclimatological gradient (moist south and dry north) result in a meridional gradient in the amplitude of the diurnal variations of (θ). This is known as the continentality effect. The winds induced by this gradient constitute the LLJ. Thus land-atmosphere coupling and land surface water and energy balance may significantly affect the climatology of the LLJ.

We are implementing a meridional chain of coupled land-PBL models that are linked by lateral energy and vapor transports. The winds and transports are themselves a function of the model prognostic (θ) at each latitude. The derivations are beyond the scope of this report but the geostrophic vertical shear and the ageostrophic component of meridional wind may be related to the model prognostic through the thermal wind equation and the Ekman spiral. For example the meriodional wind profile as a function of the model state (θ) and its gradient $\left(\frac{\partial \theta}{\partial y}\right)$ on a sloped surface $(z - z_{surf})$ is :

$$v(z) = \left(U_{g0} + \left(-\frac{U_{g0} \frac{g}{c_p}}{\theta - \frac{g}{c_p} h} - \frac{g}{f\left(\theta - \frac{g}{c_p} h\right)} \frac{\partial \theta}{\partial y} \right) z - h \right) e^{-\gamma(z - z_{surf})} \sin \gamma (z - z_{surf})$$

where U_{g0} is the large-scale geostrophic forcing (the strength of the mid-latitude westerly across the U.S. in mid-troposphere), and $\gamma = \sqrt{\frac{f}{2K_m}}$ (Kistler and Entekhabi, 1998, unpublished manuscript). The Coriolis parameter f and the eddy momentum conductivity (K_m) have been defined. The meridional wind profile may now be used in conjuction with the transport equations in order to estimate the convergence of heat and moisture into PBL cells along the LLJ. The influence of surface properties and land-atmosphere coupling on the LLJ may thus be diagnosed. Since the LLJ is known to be an important conduit of low-level moisture and energy for the Great Plains, the time-memory of anomalies and feedback mechanisms in this system may be important physical processes that help explain land contributions to the persistence of regional Central Great Plains drought and flood events.

Follow-Up Plans

The analytical land-PBL coupling model developed in this study provides the basis for testing land surface response to atmospheric forcing. Usually time-series of air micrometeorology (air temperature, air humidity, wind, downwelling solar and thermal radiation) are used to force land surface models (e.g. PILPS activity). This method of testing is very limited because the system is strongly constrained by the prescribed near-surface conditions. With this model (as demonstrated in the Verification section above), it is possible to force the land surface-PBL model solely with incoming solar radiation and wind-speed. In this manner the land-PBL system is free to respond and reveal biases and sensitivities. It will be interesting to test the PILPS and other models using a coupled PBL system. Furthermore the model from this study may be used to assimilate remote sensing measurements in order to obtain a consistent set of land and PBL thermodynamic states.

The extension of the model to include lateral transports of energy and moisture may be applied to diagnose the U.S. Great Plains Low Level Jet (LLJ). The influence of land-atmosphere coupling and land surface conditions on the LLJ may be investigated with this simple model. It is hypothesized that the meridional gradient in the diurnal amplitude of the PBL and land temperatures are key factors for the transport of vapor at low levels into the central U.S.. Persistent droughts may (e.g. 1988 Summer) may be due to a weakening of the LLJ transport which differentially forces the land surface conditions along a meridional gradient. This in turn affects the LLJ and a feedback loop is complete.

Finally Kim and Entekhabi (1997) demonstrate that the coupled land-PBL model may be used to explain traditional observations such as the value 1.26 for the Priestly-Taylor parameter α and the Bouchet-Morton complementary evaporation relationship. The analytical form of the model may be used to derive an evaporation equation based on surface temperature remote sensing.

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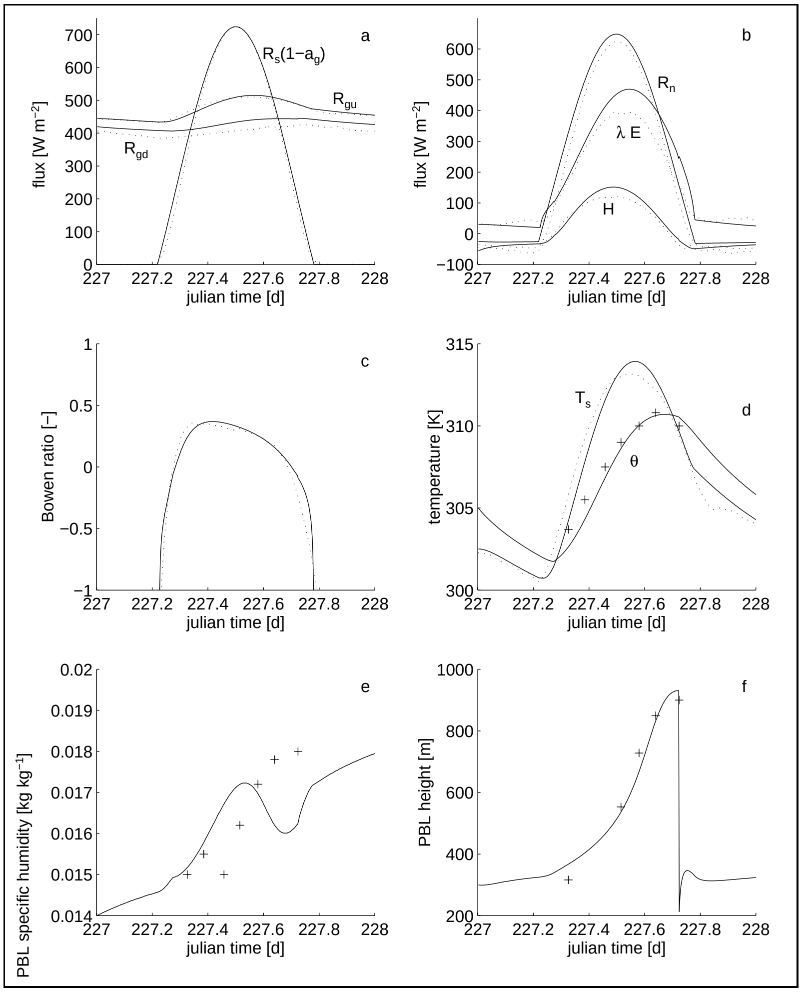

Figure 1: Verification using data collected on August 15, 1987 of FIFE. The dotted solid lines indicate the model results, the dotted lines the average surface measurements and the + markers the PBL observations. Solar noon is at 227.5.

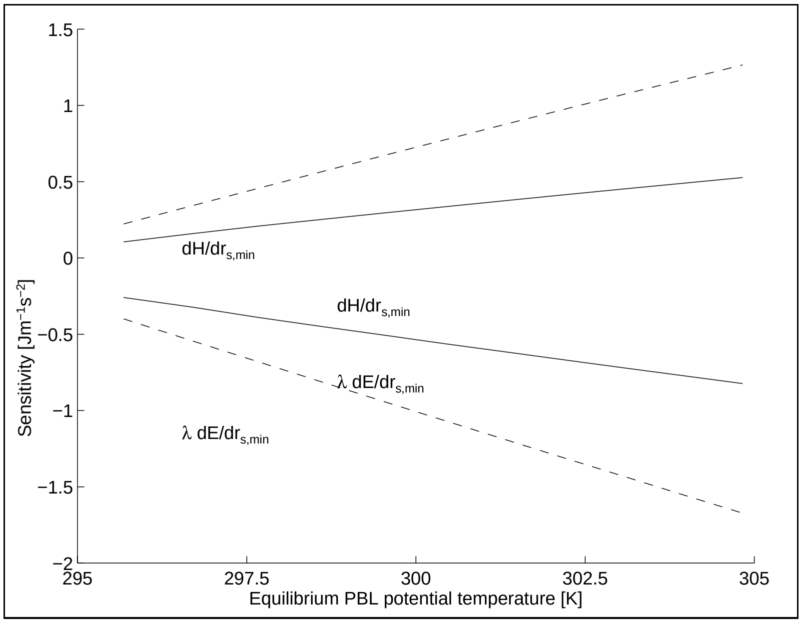

Figure 2: Sensitivity of the surface fluxes with respect to the minimal stomatal resistance $r_{s,\min}$ for the uncoupled (i.e. $\frac{d\theta}{dt} = 0$) (dashed lines) and the coupled model (solid lines).

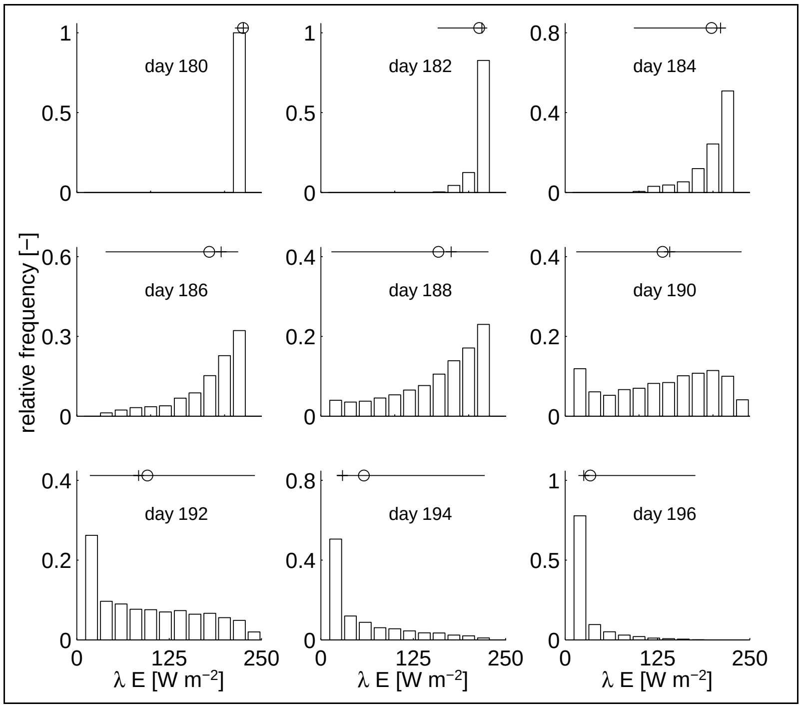

Figure 3: Histogram illustrating the time evolution of spatial heterogeneity of the daily mean latent heat flux for the clay soil. Above the histogram, the range of values of values is shown as a solid line, on which the mean value (o) and the median value (+) are indicated.